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Optimal design of the steel structure by the sequence of partial optimization

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Abstract

The article shows the possibility of using mathematical programming methods to obtain optimal solutions of building structures. As an optimization algorithm used the method optimization, based on the property of monotonicity used dependencies. Emphasizes the usefulness of mathematical modeling methods in providing integrated security construction projects and reduce the risk of the onset of failure.

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The experience of use of system engineering in various areas of engineering activities, as well as the experience of formation of system engineering of construction allows you to define the study of design problems as one of the main spheres of its application. All modern problems of construction are purely system engineering problems, and they can be divided into the following groups: technical, organizational, economic, planning, and management [1]. One of the technical problems of design includes the optimal design selection problem.

Design optimization is one of the elements of technical design. This procedure allows engineers either to find the optimal geometrical and technical characteristics of the object under the specified conditions, or to get the general

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relations and arrange the necessary methods of calculation, if they not exist [2]. At that, the process of optimal selection of main characteristics of the designed object to will become a part of the appropriate method for solving the problem, and the designs optimization will continue to be the conceptual basis of design.

When solving construction design practical problems, the selection of design decisions are often based on the engineering experience and intuition. However, when solving design problems is based on a numerical optimization algorithm, the engineering problem can be considered as purely mathematical. At that, the selection of design decisions relies on an iteration optimization process of numerical data.

The proposed by Wilde [2] optimization process used at engineering problems solving, in case when in the problem there are several variables is based on using a method of successive separate optimization. The principle of method is that several variables are operated alternately, not simultaneously, i.e. at each stage only one of the variables is used.

In the presented work the optimization process is based on using the monotonicity property of functions that prevails in the engineering problems on structural optimization.

We will solve the problem of selection of optimal sizes for horizontal cylindrical pressure tank for liquefied gas storage.

Let us assume that the volume of the tank $V = 100\text{m}^3$,

the internal pressure $p = 0.18\ \frac{\text{kN}}{\text{cm}^2}$;

We have the following variables:

S - wall thickness;

r - inner radius;

l - tank length;

t - bottom thickness.

At the first stage of the problem solving we will determine how the cost of the bottom *t* will vary depending on the variables *S, r, l*.

The total cost of manufacturing of the tank depends on *S, r, l, t,* i.e. it is necessary to minimize the function of the cost *C* (*t, S, r, l*).

Let us consider *t* and determine what varies in the object cost depending on variation in t. It is obvious that first of all the bottom cost varies. Since the bottom cost depends on the steel volume *V* multiplied by the steel cost, and the steel cost is taken as constant, the cost of the bottom varies depending on the steel volume *V* or variables *r* and *t*. Therefore, we have the cost of the bottom *C (t, r)* – the function of radius and thickness.

Since the total cost of the tank reaches its minimum when the bottom minimized in *t*, therefore we do not consider possible values of other variables at this stage of optimization.

We assume that the lower bound for the function *C (t, r)* at constant *r* can be determined as min *C (t, r)*, i.e. $C(t, r) \geq \min_t C(t, r)$ – partial function minimum in *t*, we change only *t*. The process of determination of $\min_t C(t, r)$ is called partial optimization in variable *t*.

Let us represent the total cost of the tank as a sum of the cost of the bottom *C (t, r)* and the cost of the wall *C (S, r, L)*, while the cost of the wall does not depend on *t*.

Let us consider the whole object with respect to the first variable *t*. The sequential partial optimization of the total cost of the tank with respect to *t* is to find

$$\min_t\,[C(t, r) + C(S, r, L)] = \min_t C(t, r) + \min_t C(S, r, L) = \min_t C(t, r) + C(S, r, L)$$

since the function *C (S, r, L)* does not depend on *t*.

In the presented equation the partial minimum of the total cost depends on all the variables of the problem, except *t*, because *t* is a minimand variable and the value of this variable is being optimized out of optimization of the function of the total cost.

Ultimately we are interested in the minimization of the total cost of the tank in all four variables that can be written as:

$$\min_{t,S,r,l}\,[C(t, r) + C(S, r, L)] \tag{1}$$

We can achieve the required result by determining partial minimum in t and minimizing the obtained function in all other variables. The sequence of these operations is presented as:

$$\min_{S,r,l}\ (\min_t (C(t, r) + C(S, r, L))) = \min_{S,r,l}\ (\min_t C(t, r) + C(S, r, L)) \qquad (2)$$

Two minimums of the function of general expenses (1) and (2) must be equal.

$$\min_{t,S,r,l}\ [C(t, r) + C(S, r, L)] = \min_{S,r,l}\ [\min_t C(t, r) + C(S, r, L)]$$

The right part of the equation refers to the fact that the original problem consisting of four variables should be solved at the first stage by partial optimization in t.

For this purpose it is enough to examine the function characterizing the cost of the bottom and set a limit in t of the form $t \geq H \cdot r$.

According to the Designer's Reference. Metal structures. T2. Ed. V.V. Kuznetsov [3], spherical bottoms are analyzed for stress and strains by:

$\sigma = \frac{p \cdot r \cdot \gamma_f}{2 \cdot h} \leq \gamma_c \cdot R$, from which $t = \frac{p \cdot \gamma_f \cdot r}{2 \cdot R \cdot \gamma_c}$

We assume $H = \frac{p \cdot \gamma_f}{2 \cdot R_y \cdot \gamma_c}$ then for steel 09Г2С-15 (С345) at a thickness $t = 20 \div 40$ mm;

$R_y = 29\ \frac{kN}{cm^2}$;

$\gamma_c = 0.8$ is a working condition ratio

$\gamma_f = 1.2$ is a partial safety factor for load for internal pressure.

We will receive $H = \frac{0{,}18 \cdot 1.2}{2 \cdot 29 \cdot 0.8} = 4.7 \cdot 10^{-3}$

The problem of the sequential partial optimization is to determine $\min_t C(t, r)$ taking into account constraints (strength conditions for the bottom). At that the radius r is temporarily assumed as a constant value, and H as parameter that may take on appropriate values for various design characteristics.

The cost of the bottom is proportional to the volume of metal and is an increasing function of t, which is as follows.

The steel volume of the bottom is $V = 2 \cdot \pi \cdot r^2 \cdot t$,

Let us set the constant 2π as a parameter of the cost of the bottom C_t,

Thus, $C(t, r) = C_t \cdot r^2 \cdot t$,

Therefore, $\min_t C(t, r) = C_t \cdot r^2 (\min_t t)$, so to minimize the cost of the bottom it is necessary to make its thickness t as small as possible, i.e. as close to the lower bound $t \geq H \cdot r$ as possible.

Thus, the minimum cost of the bottom is:

$\min_t C(t, r) = C_t \cdot r^2 \cdot H \cdot r = (C_t \cdot H) \cdot r^3$,

where $(C_t \cdot H)$ is a parameter.

At the next stage of solving of the problem we will make a partial optimization of the total cost of the tank in the wall thickness S.

Other factors being equal (t, r, l are constant) the cost of manufacturing of the tank wall increases as S increases. Therefore, the value S should be done as small as possible. Let us set the restriction for the strength of the tank wall. According to the Designer's Reference [3] the voltage in the tank wall will be:

$$\sigma = \frac{\gamma_f \cdot p \cdot r}{S} \leq R_{wy} \cdot \frac{\gamma_c}{\gamma_n},$$

where $R_{wy} = R_y$ is a rated design resistance of a weld at physical monitoring methods;
$\gamma_c = 0.8$ is a working condition factor;
$\gamma_n = 1.1$ is a safety factor for the purpose;
$\gamma_f = 1.2$ is a partial safety factor for the load for internal pressure;
S - wall thickness;

$$S = \frac{\gamma_f \cdot p \cdot \gamma_n}{R_y \cdot \gamma_c} \cdot r$$

Let us assume the imposed restrictions in the form $S \geq K_s \cdot r$, where

$$K_s = \frac{\gamma_f \cdot p \cdot \gamma_n}{R_y \cdot \gamma_c} = \frac{1.2 \cdot 1.1 \cdot 0.18}{29 \cdot 0.8} = 10.2 \cdot 10^{-3}$$

The function of the cost of the tank wall will reach its minimum, when the value S corresponds to the exact lower bound, i.e. $S_{min} = K_s \cdot r$,

Therefore,

$$\min_{S,r,l} [C(S, r, l)] = \min_{r,l} [\min_{S} C(S, r, l)] = \min_{r,l} [C(S_{min}, r, l)] = \min_{r,l} [C(K_s r, r, l)]$$

The cost of the wall material is proportional to its volume, which is equal to $2\pi r \cdot l \cdot s$. Let us denote 2π as Cs as a parameter of the wall cost.

We have $C(S, r, l) = C_s \cdot r \cdot l \cdot S$,

To minimize S, we substitute $S_{min} = K_s \cdot r$, then the cost of the tank is minimized in S and will be

$C(S, r, l) = C_s \cdot r \cdot l \cdot K_s \cdot r = (C_s \cdot K_s) \cdot r^2 \cdot l$ which is an increasing function of r and l.

The result of partial optimization of two variables will be as follows:

$$\min_{t,S,r,l} [C(t, r) + C(S, r, l)] = \min_{r,l} [\min_{t \geq H \cdot r} C(t, r) + \min_{S \geq Ks \cdot r} C(S, r, l)] =$$

$$= \min_{r,l} [(C_h \cdot H) \cdot r^3 + (C_s \cdot K_s) \cdot r^2 \cdot l] \tag{3}$$

For minimization in r and in l, it is necessary to consider the remaining constraints.

The tank volume will be:

$$V = \pi \cdot r^2 \cdot l \tag{4}$$

One can see that the functions (3) and (4) are increased as r and l increase. Thus, the more the tank volume, the more its cost. The tank with minimum permissible volume $V = \pi \cdot r^2 \cdot l$ corresponds to the minimum cost.

From the equation of the tank volume you can obtain an explicit expression for l, at that r is unknown.

$$l = \frac{V}{\pi \cdot r^2}$$

The elimination of l from the relation (3) will lead to the dependence:

$$C = \min_{r,l} \left[(C_t \cdot H) \cdot r^3 + (C_s \cdot K_s) \cdot r^2 \cdot \frac{V}{\pi \cdot r^2} \right] = (C_t \cdot H) \cdot r^3 + \frac{V}{\pi} \cdot (C_s \cdot K_s),$$

we got an equation with r in the first summand.

Since the factor $(C_t \cdot H) \cdot r^3$ is positive, and the factor $\frac{V}{\pi} \cdot (C_s \cdot K_s)$ does not depend on r, the total cost of the tank is an increasing function of r. Thus, the radius of the tank should be as small as possible. At the same time from the formula of the tank volume $V = \pi \cdot r^2 \cdot l$ it is seen that the value of the radius is bounded from below, because there is an upper bound of the wall length - the maximum value L_{max}.

$r = \sqrt{\frac{V}{\pi \cdot l}}$; $l = \frac{V}{\pi \cdot r^2} \leq L_{max}$

Therefore, we assume $l_* = L_{max}$, where l_* is the value of this variable at which a minimum of the function being optimized is achieved.

We have two constraints on the bottom thickness t, the lower bound is determined by the strength condition, the upper bound – by the limitation of the total tank length L_{max}. As the cost of the bottom is increased with a rise of t, at the minimum point as an active constraint there should be used the greatest lower bound, i.e. $t_* = H \cdot r_*$. For partial optimization in r it is necessary to use a limiting value of the tank volume V as an active constraint.

Thus, there are four constraints:

For wall thickness $S \geq K_s \cdot r$

For bottom thickness $t \geq H \cdot r$

For the dimensions, which determine the volume $V = \pi \cdot r^2 \cdot l$

For the overall length of tank $l \leq Lmax$

Finally we have that the definition of an optimum design is ensured by using the following equations:

$l_* = L_{max}$ - the optimal value of the length of the tank l;

$r_* = \sqrt{\frac{V}{\pi \cdot L_{max}}}$ - the optimal value of the radius of the wall r;

$t_* = H \cdot r_*$ - the optimal value of the bottom thickness t;

$S_* = K_s \cdot r_*$ - the optimal value of the wall thickness.

The following main design characteristics are set in this example

L = 1200 cm; V = 100 m3, $H = 4.7 \cdot 10^{-3}$; $K_s = 10.2 \cdot 10^{-3}$,

Then the variables have the following optimal values.

l_* = 1200 cm; $r_* = \sqrt{\frac{100 \cdot 10^6}{3.14 \cdot 1200}} = 163$ cm.

That corresponds to D = 326 cm ≈ 3.25 m - therefore a constraint on the observance of transport dimensions is performed.

$t_* = 4.7 \cdot 163 = 0.76$ cm = 8 mm;

$S_* = 10.2 \cdot 10^{-3} \cdot 163 = 17$ mm.

Concluding

The considered in this article method of partial optimization by Wilde, is based on the monotonicity of the dependencies, which is a quite simple and at the same time reliable theoretical basis of the method.

We have designed the tank on the basis that its length must correspond to the maximum permissible value determined by the overall constraints, and the other dimensions are determined by the requirements of design standards, and each constraint is considered as a strict equality. At designing of building structures, which are fully conditioned by the constraints, you can use the inherent property, allowing you to solve the problem without detailed information on the economic characteristics of the designed construction - the monotonicity property of the function.

References

[1] Gusakov, A.A., System engineering. M.: Fund New Millennium, 2002, 768 pages.
[2] Wilde, D., Optimal design: Translation from English, M.: Mir, 1981, 272 pages.

[3] Kuznetsov, V.V., Metal structures. In 3 volumes. Designer's Reference. M.: ASV, 1998, 576 pages.
[4] Volkov A.A., Vasil'kin A.A. Razvitie metodologii poiska proektnogo resheniya pri proektirovanii stroitel'nykh metallokonstruktsiy [Development of methodology of search of the design decision at design of building steel structures] // Vestnik MGSU. 2014. №9. p. 123-137.
[5] Volkov A., Chelyshkov P., Sedov A. Application of computer simulation to ensure comprehensive security of buildings. Applied Mechanics and Materials Vols. 409-410 (2013) pp 630-633 © (2013) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.409-410.630"
[6] Volkov A., Sedov A., Chelyshkov P. Usage of building information modelling for evaluation of energy efficiency. Applied Mechanics and Materials Vols. 409-410 (2013) pp 630-633 © (2013) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.409-410.630"
[7] Volkov A., Sedov A., Chelyshkov P. Modeling the thermal comfort of internal building spaces in cocial buildings . Procedia Engineering 00 (2014) 000–000
[8] Volkov A., Sedov A., Chelyshkov P. The criteria's set with invariant design building elements on the base of three imputations: "Convenience", "Safety" and "Energy-efficiency". Procedia Engineering 00 (2014) 000–000
[9] Volkov A., Sedov A., Chelyshkov P., Doroshenko A. Using CAD for selecting different ACS engineering systems of buildings and structures in the presence of interference and restrictions . Applied Mechanics and Materials Vols. 580-583 (2014) pp 3231-3233 © (2014) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.580-583.3231
[10] Volkov A., Sedov A., Chelyshkov P., Kulikova E. Modeling the thermal comfort of internal building spaces in hospital . Applied Mechanics and Materials Vols. 584-586 (2014) pp 753-756 © (2014) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.584-586.753
[11] Volkov A., Sedov A., Chelyshkov P., Kulikova E. Modeling the thermal comfort of internal building spaces in kindergarten. Applied Mechanics and Materials Vols. 584-586 (2014) pp 757-760 © (2014) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.584-586.757
[12] Volkov A., Sedov A., Chelyshkov P., Kulikova E. Modeling the thermal comfort of internal building spaces in school. Applied Mechanics and Materials Vols. 584-586 (2014) pp 757-760 © (2014) Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/AMM.584-586.757
[13] Volkov A., Chelyshkov P., Sedov A. SCENARIO buidings' SIMULATION IN THE COMPLEX SECURITY TASKS. 3rd International Conference on Mechatronics, Robotics and Automation (ICMRA 2015), pp. 1193-1196, doi:10.2991/icmra-15.2015.230
[14] Volkov A., Chelyshkov P., Sedov A. THE SCENARIO-BASED VERIFICATION METHOD OF THE BUILDINGS' ENERGY BALANCE: THE ANALYZED PARAMETERS AND IMPLEMENTATION ALGORITHM. 3rd International Conference on Mechatronics, Robotics and Automation (ICMRA 2015), pp. 1193-1196, doi:10.2991/icmra-15.2015.230
[15] Volkov A., Sedov A., Chelyshkov P., Pavlov A., Kievskiy L. Promising energy and ecological modeling in computer-aided design. International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 3 (2016) pp 1645-1648 © Research India Publications. http://www.ripublication.com